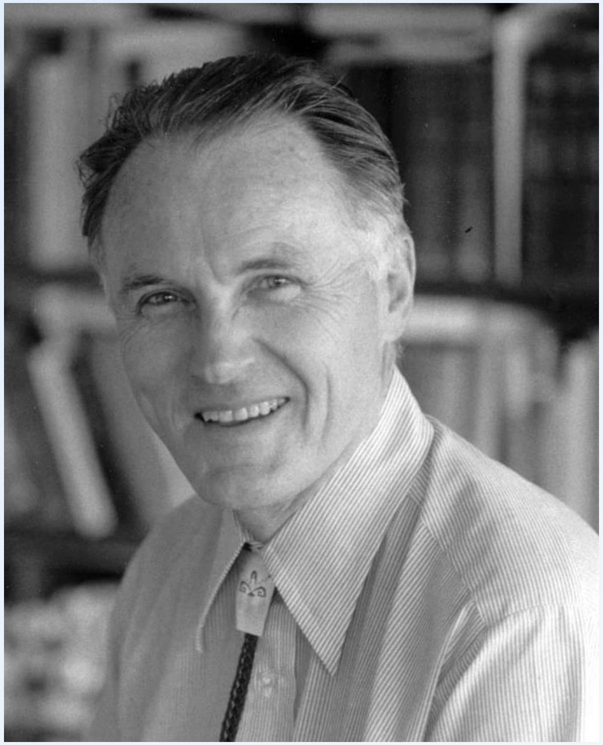
Horace W. Babcock
(1912-2003)

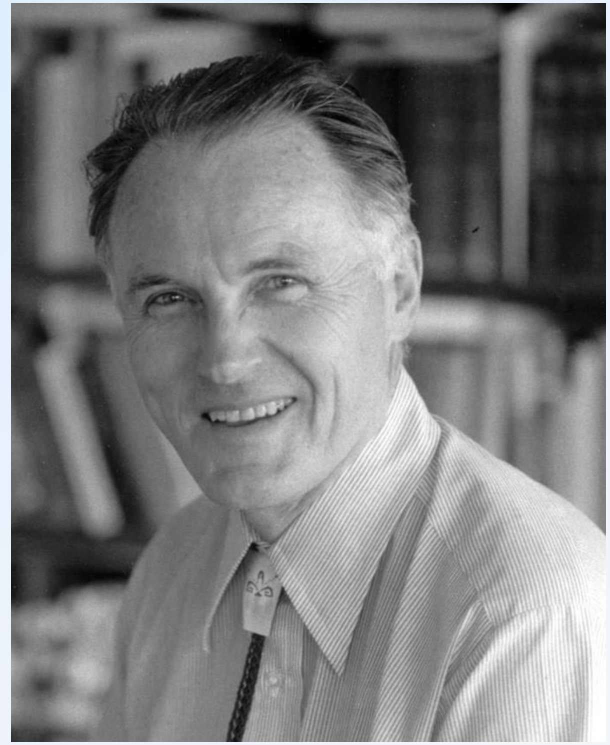


Robert B. Leighton
(1919-1997)

The Babcock-Leighton solar dynamo

M. Schüssler & R.H. Cameron
Max Planck Institute for Solar System Research

Horace W. Babcock
(1912-2003)

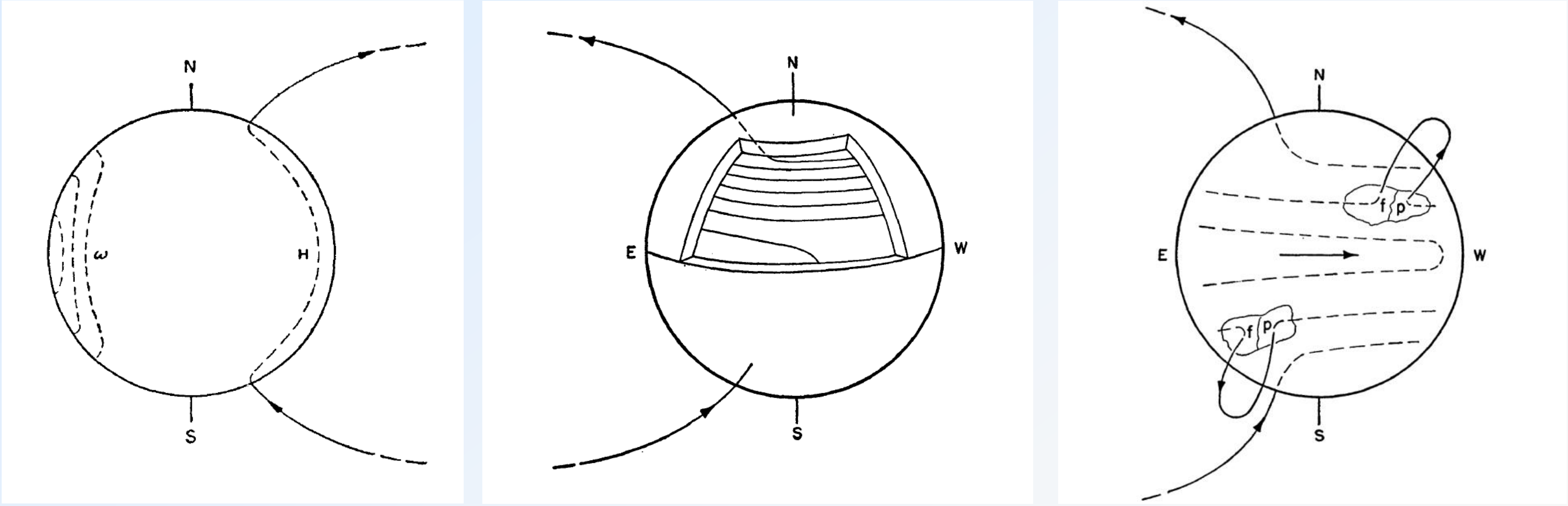


Robert B. Leighton
(1919-1997)

The Babcock-Leighton solar dynamo captures the physical essence of the dynamo process.

BL scenario in a nutshell

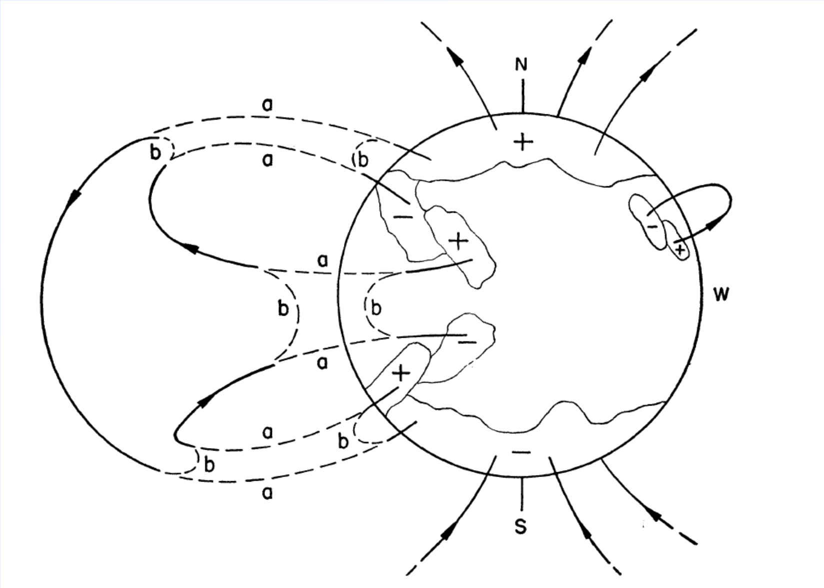
1) **The poloidal magnetic flux connected to the polar field is wound up by latitudinal differential rotation to produce the toroidal field, whose emergence later produces active regions.**



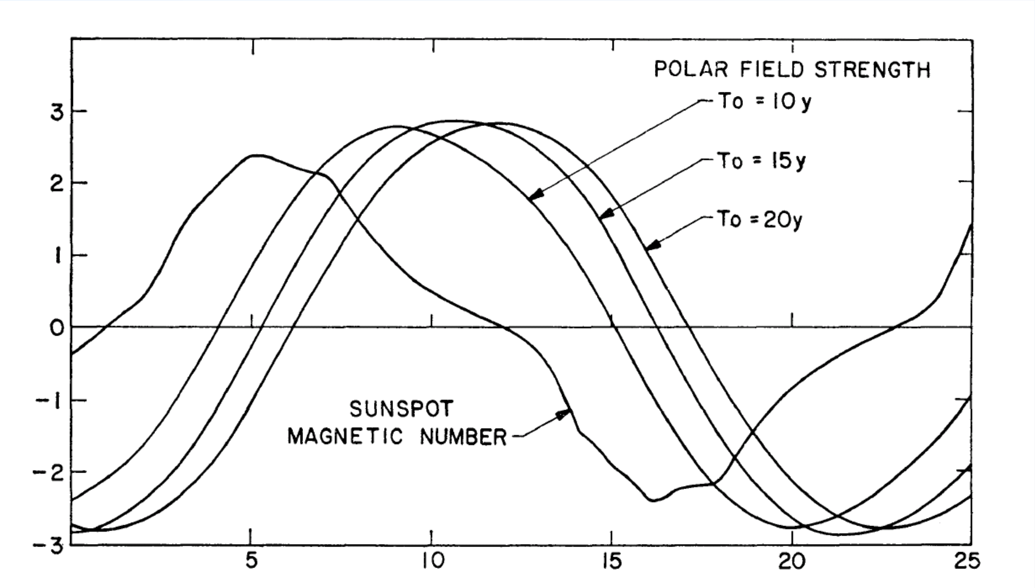
Babcock (1961)

BL scenario in a nutshell

2) **The builup and reversals of the polar field result from the surface evolution of the magnetic flux emerging in systematically tilted active regions.**



Babcock (1961)

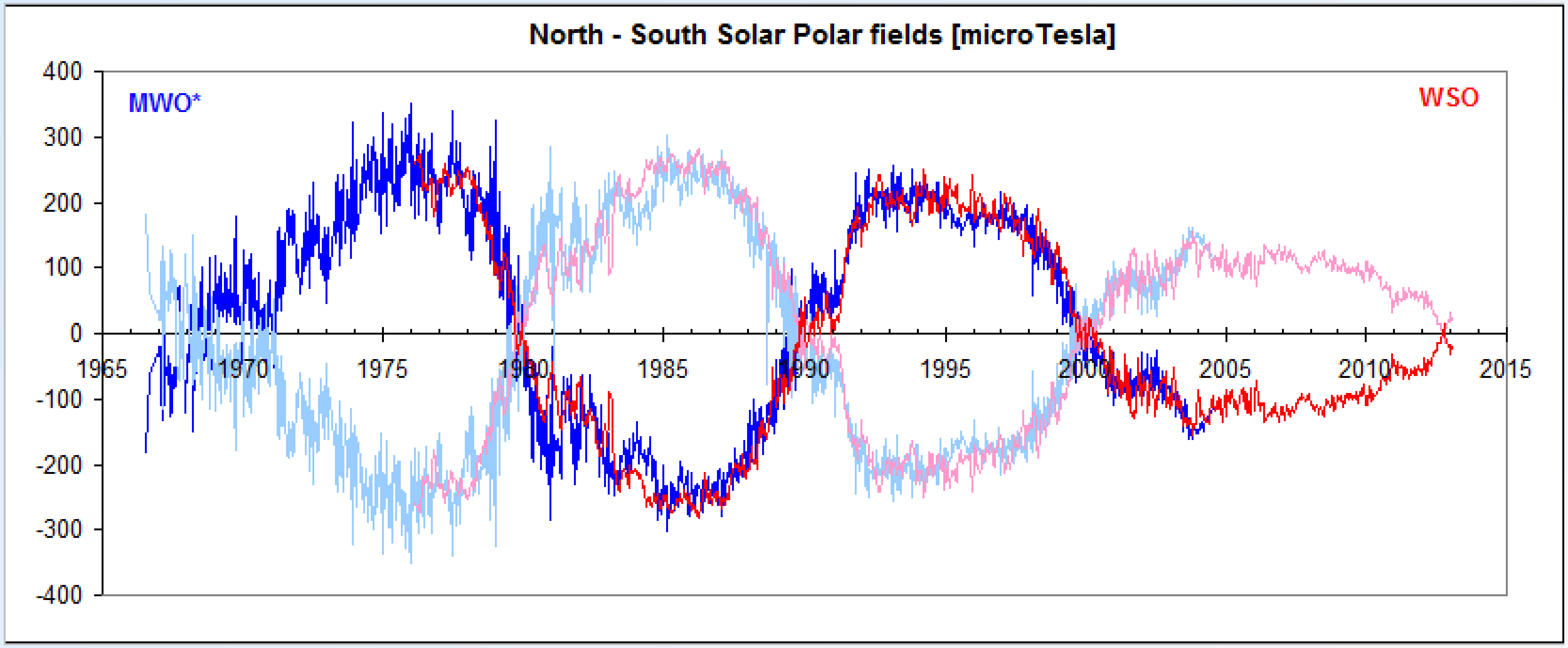


Leighton (1964)

⇒ **WYSIWYG** dynamo, i.e. ***What You See Is What You Get***

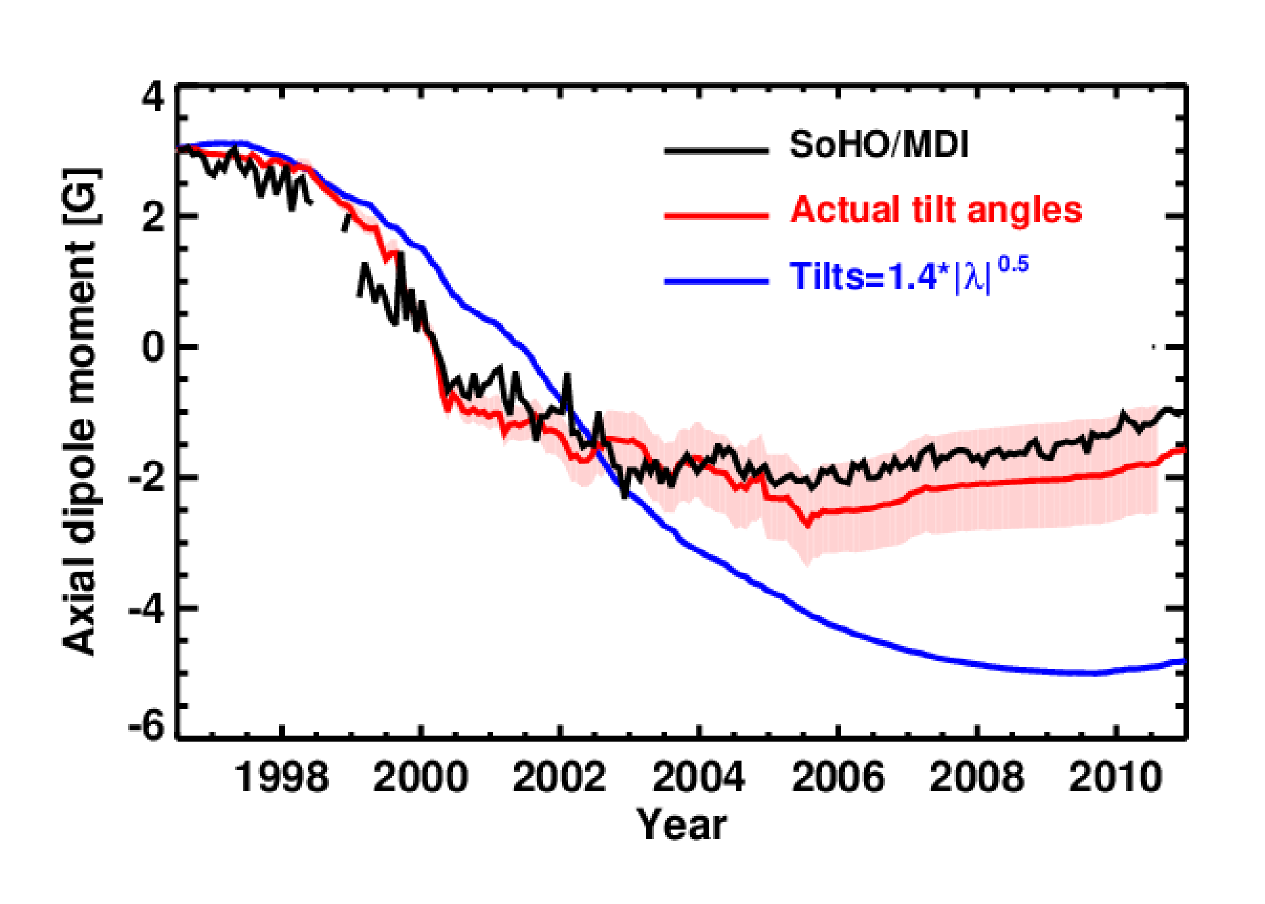
Pieces of evidence

1) Surface flux transport simulations reproduce the observed evolution of the polar fields



Pieces of evidence

1) Surface flux transport simulations reproduce the observed evolution of the polar fields

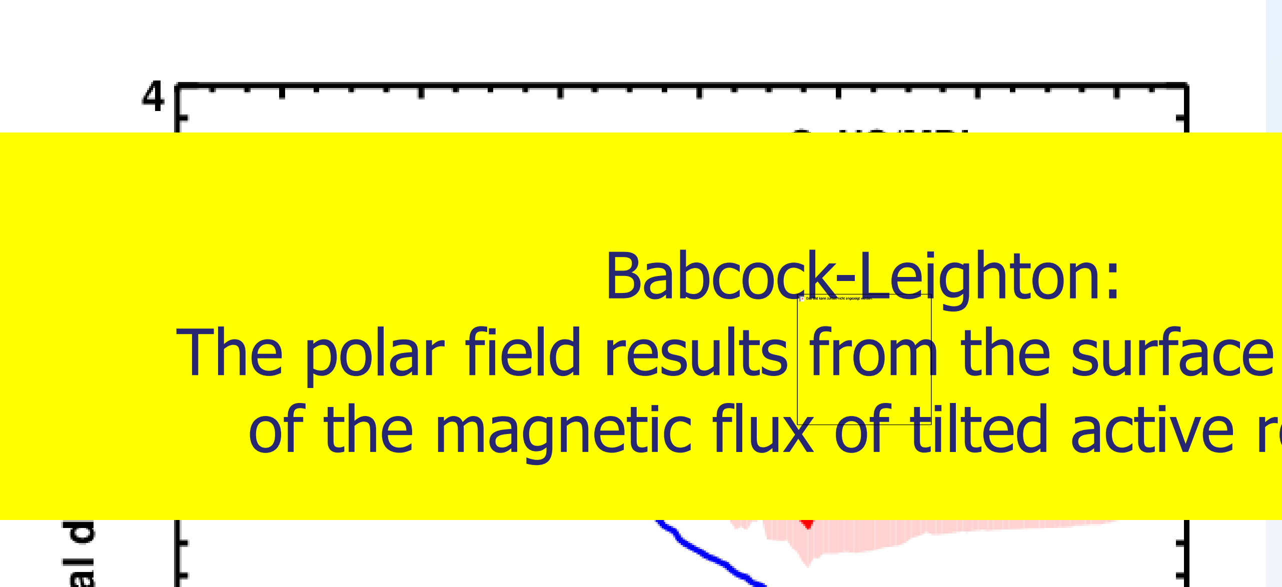


Axial dipole moment

Jiang et al. (submitted)

Pieces of evidence

1) Surface flux transport simulations reproduce the observed evolution of the polar fields



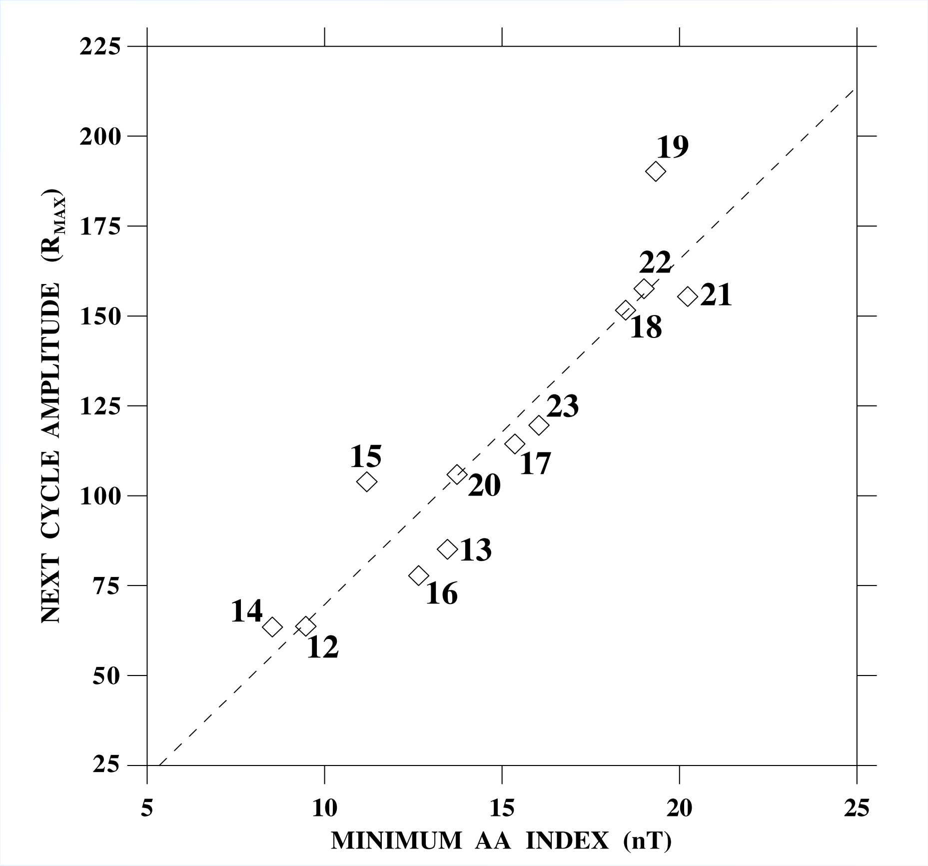
Babcock-Leighton:
The polar field results from the surface evolution of the magnetic flux of tilted active regions.

Note:
The only sources of magnetic flux for the SFT simulations are bipolar active regions, no ephemeral regions or smaller features.

Jiang et al. (submitted)

Pieces of evidence

2) The polar fields at the end of a cycle are strongly correlated with the strength of the next cycle.



p = 0.0026

Wang & Sheeley (2009)

Geomagnetic aa-Index @ solar minima

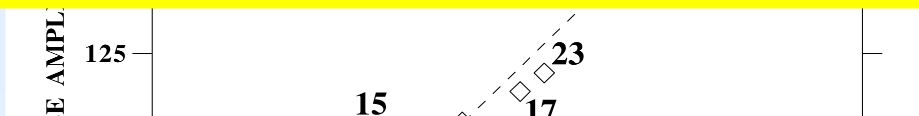
(→ proxy for open heliospheric flux & polar fields)

Pieces of evidence

2) The polar fields at the end of a cycle are strongly correlated with the strength of the next cycle.

Babcock-Leighton:
The polar field represents the poloidal source for the toroidal field, whose emergence produces active regions.

?



But:
Correlation does not imply causation…
Polar field and „poloidal field of the dynamo"
could be produced by the same process.

Geomagnetic aa-Index @ solar minima

(→ proxy for open heliospheric flux & polar fields)

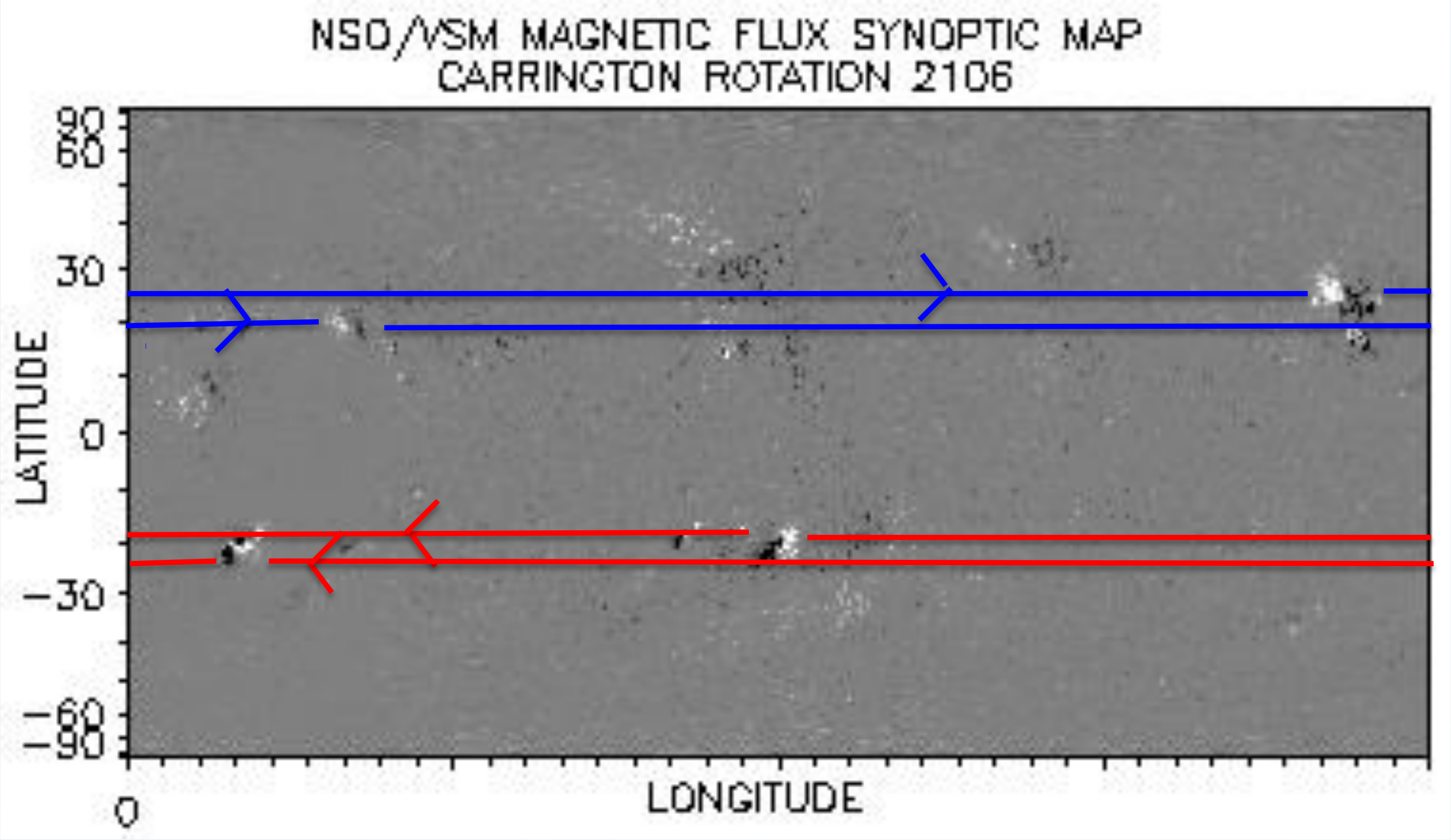
The crucial question

Q: What is the relevant poloidal field for the solar dynamo?

Steps toward an answer

Q: What is the relevant poloidal field for the solar dynamo?

Hale's polarity laws imply that bipolar magnetic regions result from a **large-scale toroidal field of fixed orientation** in each hemisphere during a cycle.



Steps toward an answer

Q: What is the relevant poloidal field for the solar dynamo?

Hale's polarity laws imply that bipolar magnetic regions result from a **large-scale toroidal field of fixed orientation** in each hemisphere during a cycle.

→ Need to consider the **net toroidal flux** in a hemisphere, determined from the azimuthally averaged induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{U} \times \mathbf{B} + \langle \mathbf{u} \times \mathbf{b} \rangle - \eta \nabla \times \mathbf{B} \right)$$

B(r,θ): azimuthally averaged magnetic field,
U(r,θ): azimuthally averaged velocity,
u, **b** : fluctuations w.r.t. azimuthal averages,
η : molecular diffusivity

Steps toward an answer

Determine toroidal flux in the northern hemisphere by integrating over a meridional surface Σ and applying Stokes′ theorem:

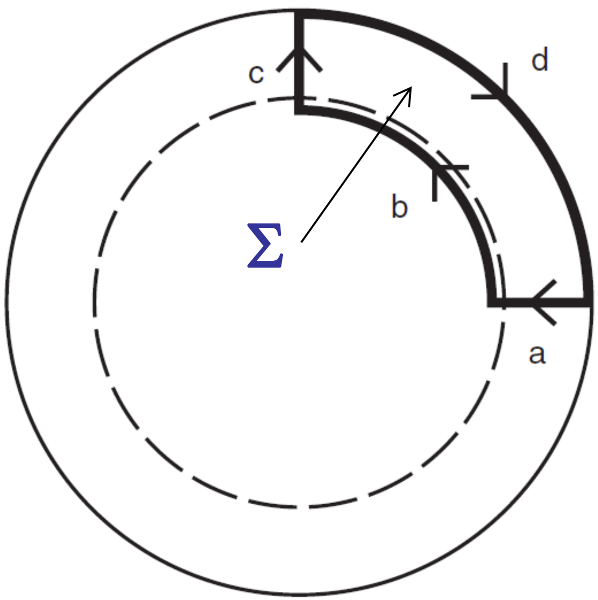
$$\frac{\mathrm{d}\Phi_{\mathrm{tor}}^{\mathrm{N}}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\int_{\Sigma} B_{\phi}\,\mathrm{d}S\right)$$

$$= \int_{\delta\Sigma}\left(\mathbf{U}\times\mathbf{B} + \langle\mathbf{u}\times\mathbf{b}\rangle - \eta\nabla\times\mathbf{B}\right)\cdot\mathrm{d}\mathbf{l}$$

Rotation dominates: $U = U_{\phi}\,\hat{\phi} = (\Omega r\sin\theta)\hat{\phi}$

$\langle\mathbf{u}\times\mathbf{b}\rangle$ reduces to „turbulent" diffusivity, η_t

$$\frac{\mathrm{d}\Phi_{\mathrm{tor}}^{\mathrm{N}}}{\mathrm{d}t} = \int_{\delta\Sigma}(\mathbf{U}\times\mathbf{B} - \eta_t\nabla\times\mathbf{B})\cdot\mathrm{d}\mathbf{l}$$

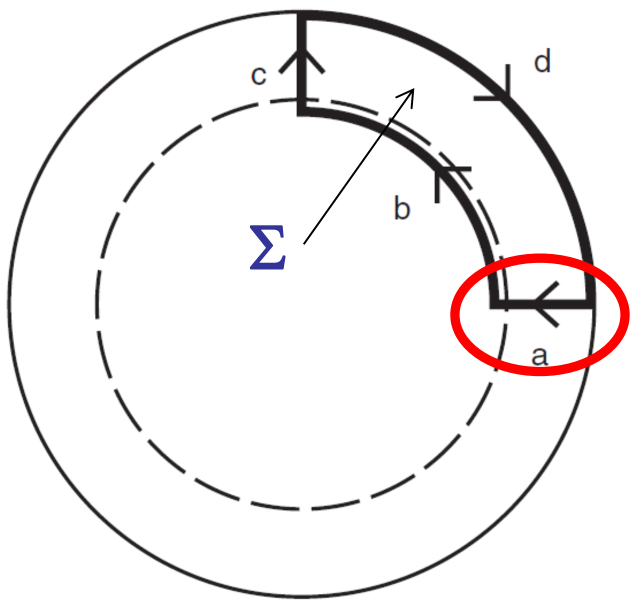


Meridional cut

Steps toward an answer

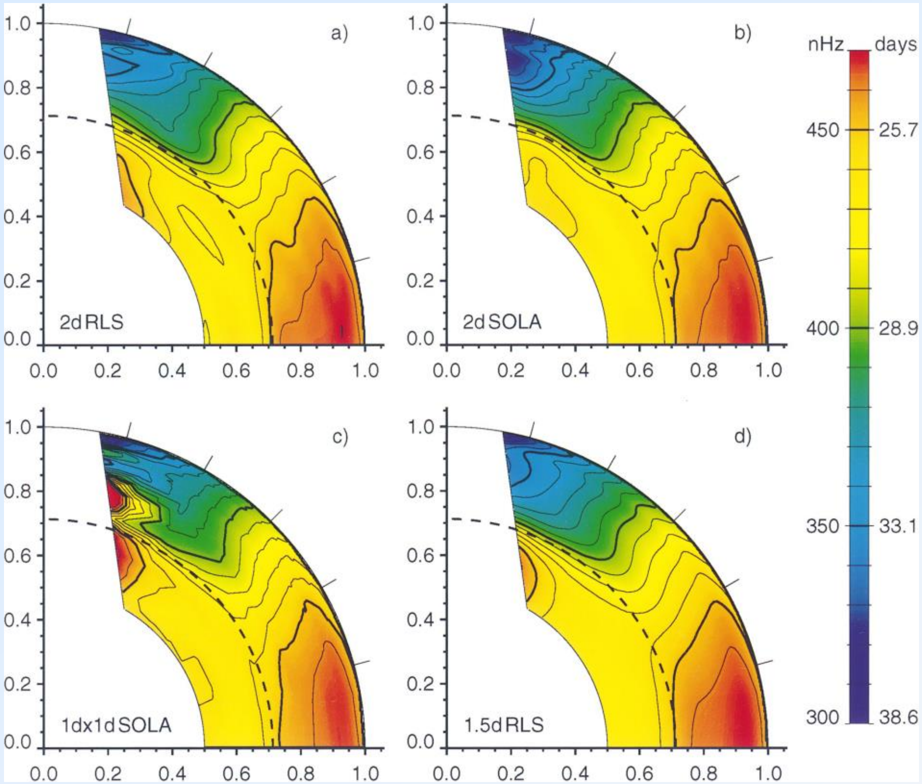
Consider $\int_{\delta\Sigma} (\mathbf{U} \times \mathbf{B}) \cdot d\mathbf{l}$

Part a: Ω almost independent of r in the equatorial plane: $\Omega(r, \pi/2) = \Omega_{eq}$

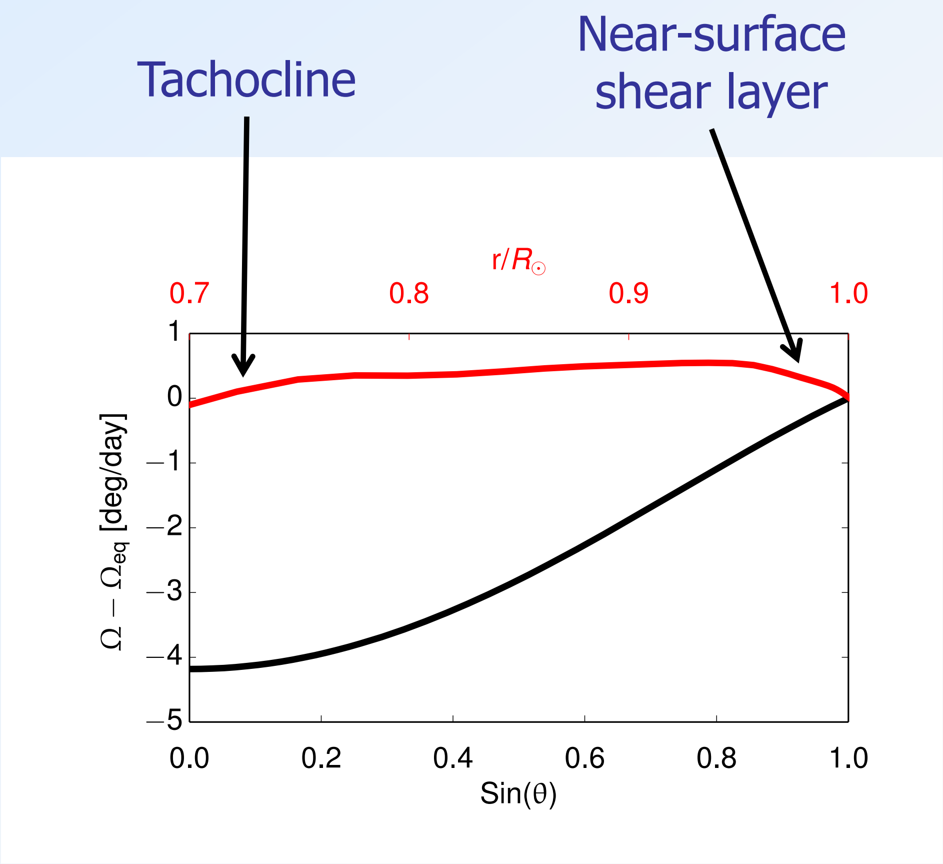


Meridional cut

Helioseismology



Schou et al. (1998)



The contribution to Φ_{tor} by radial diff. rotation is a few % of that of latitudinal diff. rotation.

Steps toward an answer

Consider $\int_{\delta\Sigma} (\mathbf{U} \times \mathbf{B}) \cdot d\mathbf{l}$

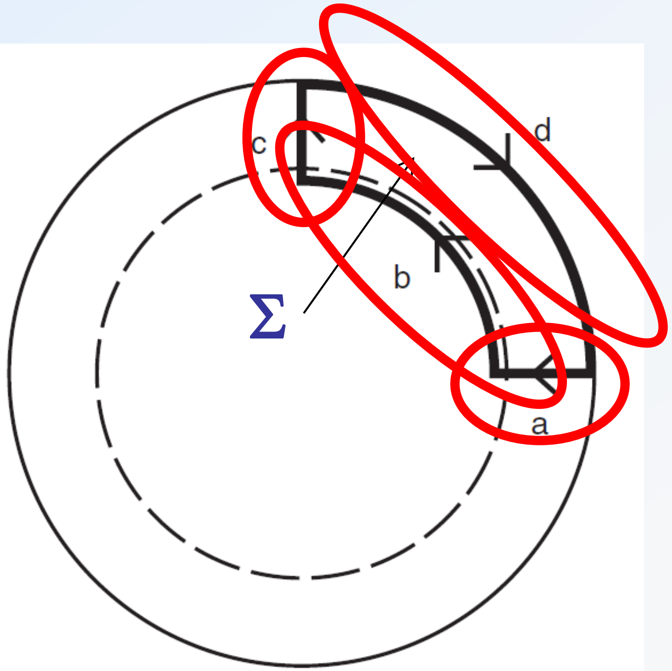
Part a: Ω almost independent of r in the equatorial plane: $\Omega(r, \pi/2) = \Omega_{eq}$

Move in a frame rotating with Ω_{eq}
$\rightarrow$ no contribution

Part b: below convection zone, B=0
$\rightarrow$ no contribution

Part c: along the axis, B=U=0
$\rightarrow$ no contribution

Part d: the surface part of the integration provides the only significant contribution



Meridional cut

Steps toward an answer

$$\frac{\mathrm{d}\Phi_{\mathrm{tor}}^{\mathrm{N}}}{\mathrm{d}t} = \int_{\delta\Sigma} (\mathbf{U} \times \mathbf{B} - \eta_{\mathrm{t}} \nabla \times \mathbf{B}) \cdot \mathrm{d}\mathbf{l}$$

$$\int_{\delta\Sigma} (\mathbf{U} \times \mathbf{B}) \cdot \mathrm{d}\mathbf{l} = \int_0^{\pi/2} U_\phi B_r R_\odot \mathrm{d}\theta$$
$$= \int_0^1 (\Omega - \Omega_{\mathrm{eq}}) B_r R_\odot^2 \mathrm{d}(\cos\theta)$$

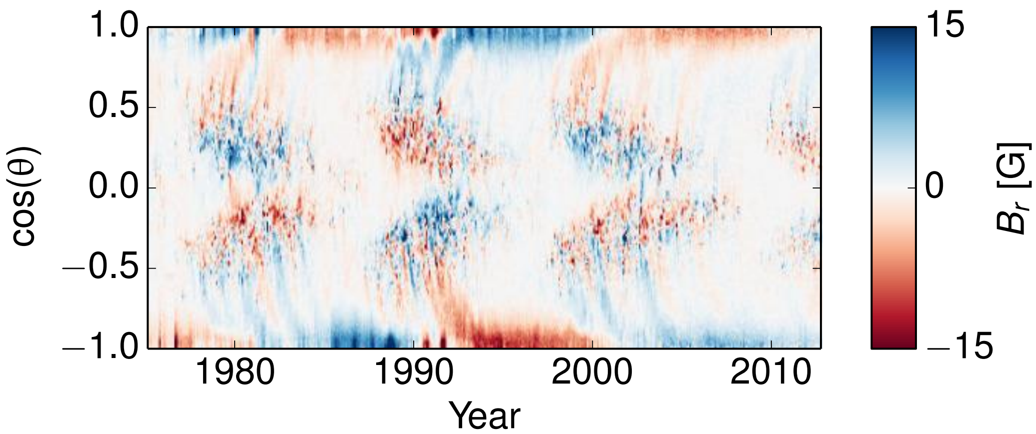
An analoguous expression is valid for the southern hemisphere.

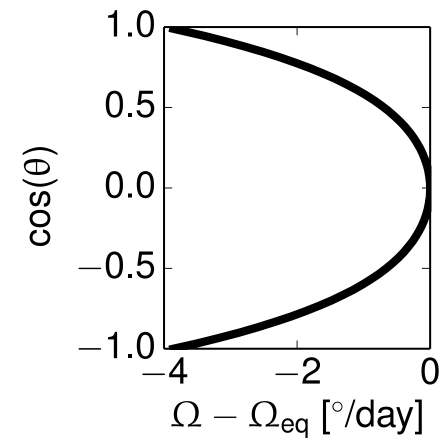
Result: the amount of net toroidal flux is determined by the surface distribution of emerged magnetic flux and the latitudinal differential rotation.

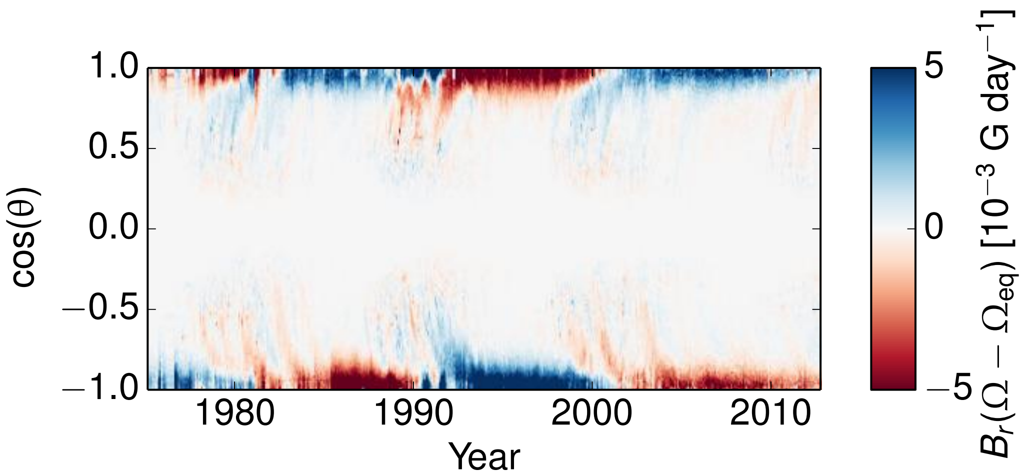
Steps toward an answer

Quantitative evaluation: use Kitt Peak synoptic magnetograms (1975-) and the observed surface differential rotation

$$\int_{\delta\Sigma} (\mathbf{U} \times \mathbf{B}) \cdot \mathrm{d}\mathbf{l} = \int_{\pi/2}^{0} U_\phi B_r R_\odot \mathrm{d}\theta = \int_{1}^{0} (\Omega - \Omega_{\mathrm{eq}}) B_r R_\odot^2 \, \mathrm{d}(\cos\theta) \,,$$





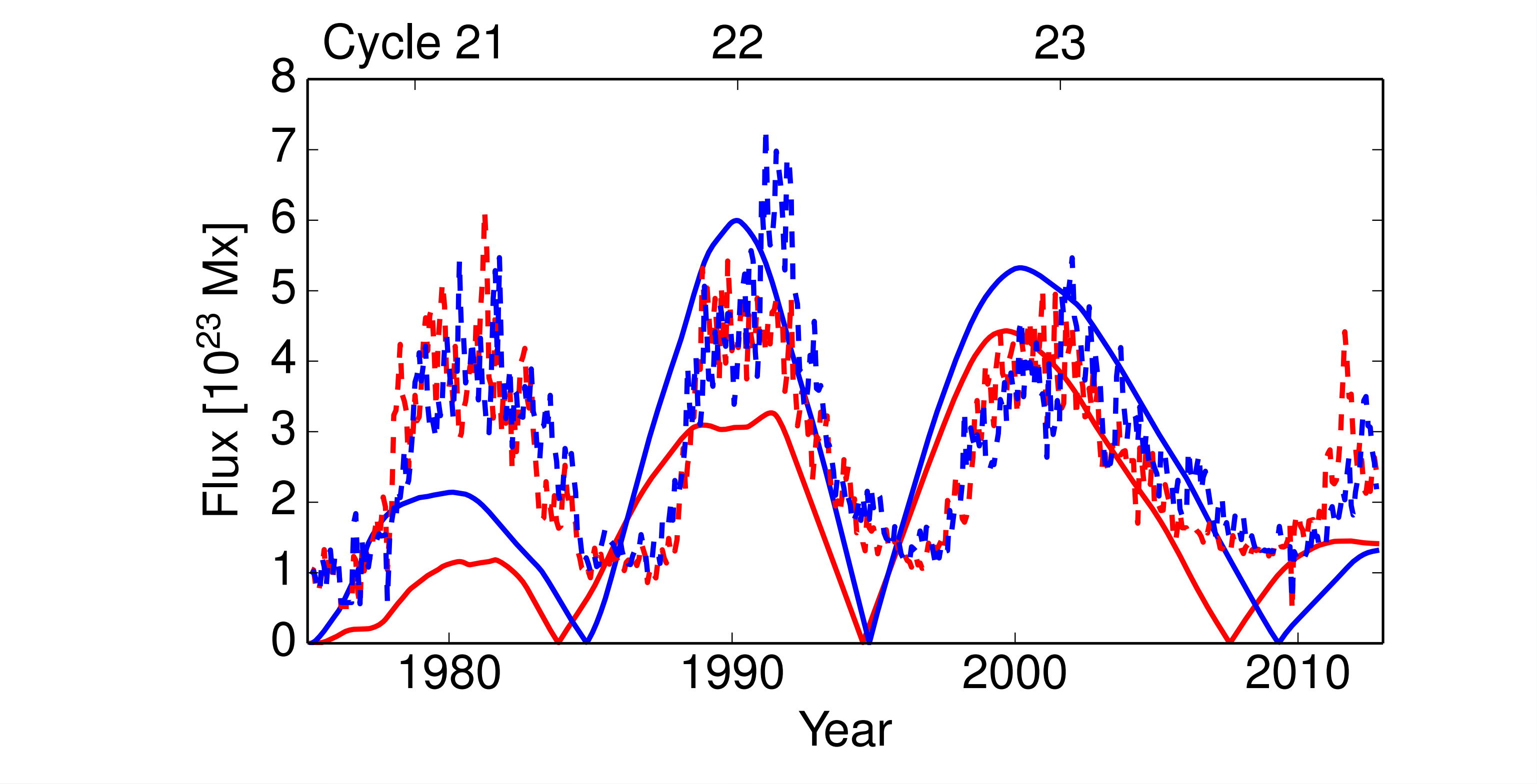


$$(\Omega - \Omega_{\mathrm{eq}}) B_r.$$

The integrand is dominated by the contribution from the polar fields.

Steps toward an answer

Time integration of $$\frac{d\Phi_{tor}^{N}}{dt} = \int_0^1 (\Omega - \Omega_{eq}) B_r R_\odot^2 \, d(\cos\theta)$$



solid: modulus of the net toroidal flux

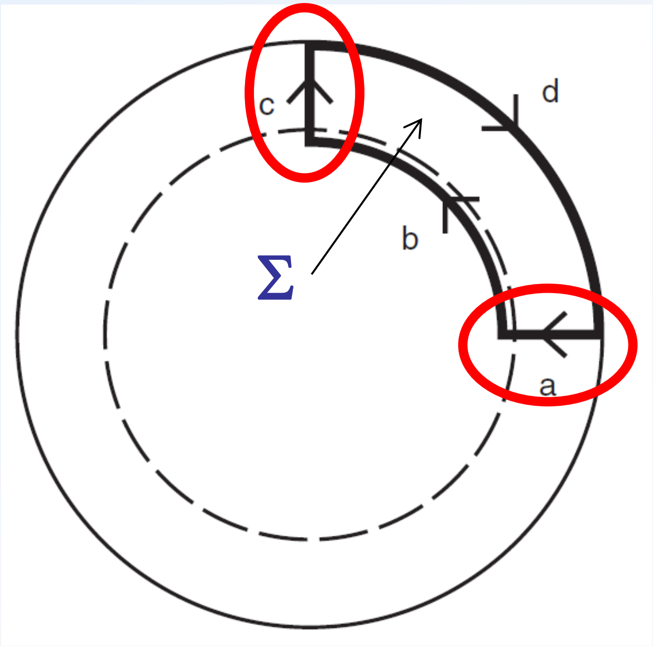
dashed: total unsigned surface flux, $\Phi_U = \int |B_r| dA$ (KPNO synoptic magnetograms)

red: northern hemisphere, blue: southern hemisphere

Random walk & „turbulent" diffusivity

Generally we have

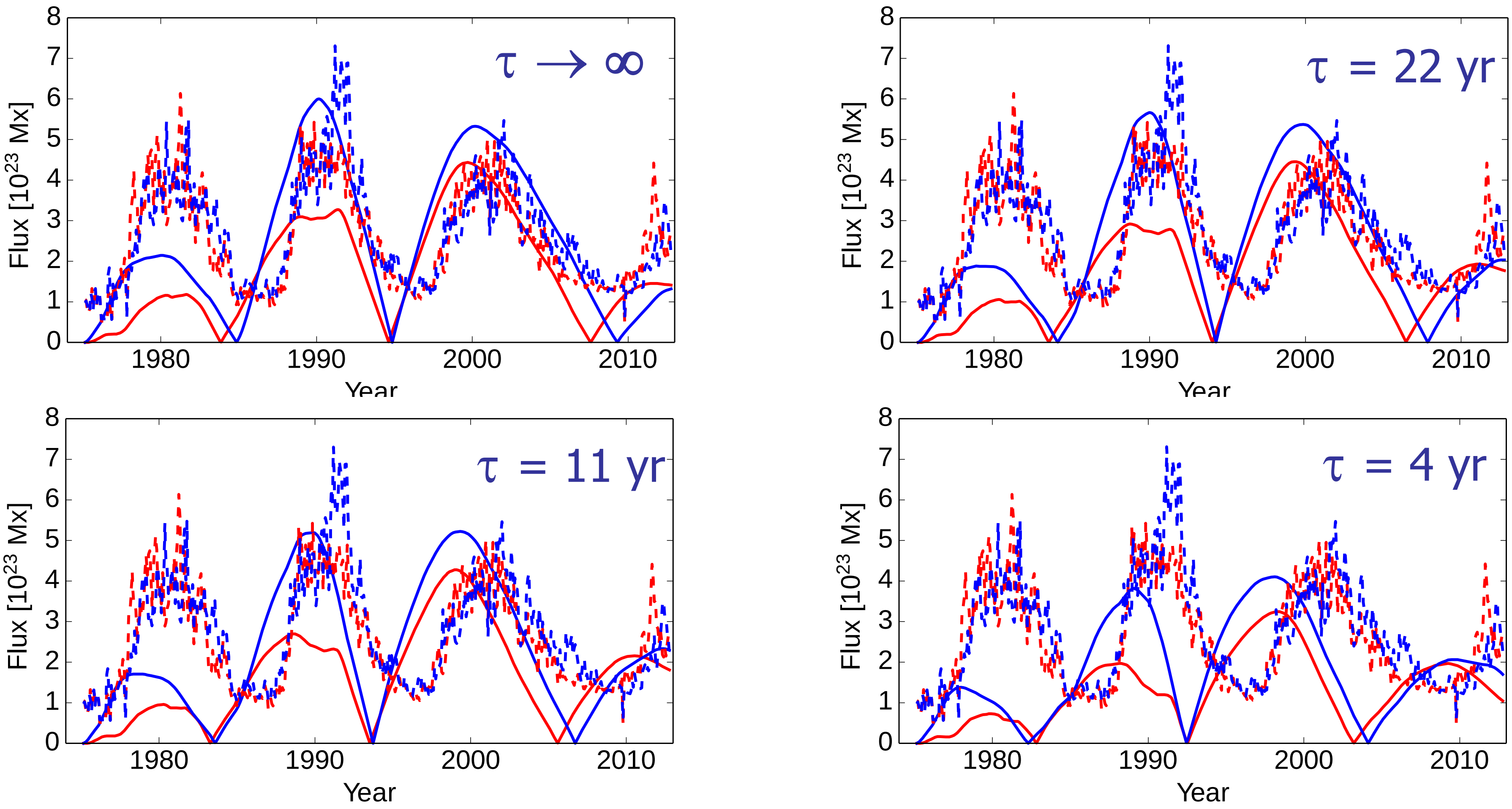
$$\frac{d\Phi^{N}_{tor}}{dt} = \int_{\delta\Sigma} (\mathbf{U} \times \mathbf{B} - \eta_t \nabla \times \mathbf{B}) \cdot \mathbf{dl}$$



„Turbulent" diffusion (flux loss at the axis and random-walk transport over the equator) is crudely approximated by an exponential decay term:

$$\frac{d\Phi^{N}_{tor}}{dt} = \int_0^1 (\Omega - \Omega_{eq}) B_r R_\odot^2 \, d(\cos\theta) - \frac{\Phi^{N}_{tor}}{\tau}$$

Effect of the decay term



Answering the question

Q: What is the relevant poloidal field for the solar dynamo?

A: The magnetic flux connected to the polar field represents the dominating poloidal source of the net toroidal flux which emerges in the subsequent cycle.

Any other poloidal field (hidden in the convection zone) leads to equal amounts of eastward and westward toroidal flux and thus does not contribute to the net toroidal flux required by Hale's polarity laws, i.e. does not play a significant role in the solar dynamo process.

Babcock-Leighton:
The polar field represents the poloidal source for the toroidal field, whose emergence produces active regions.

!

Conclusions

- The solar dynamo operates according to the WYSIWYG scenario laid out by H.W. Babcock and R.B. Leighton in the 1960s:

  1) polar field is generated by surface transport of flux from tilted active regions
     ← Surface Flux Transport simulations

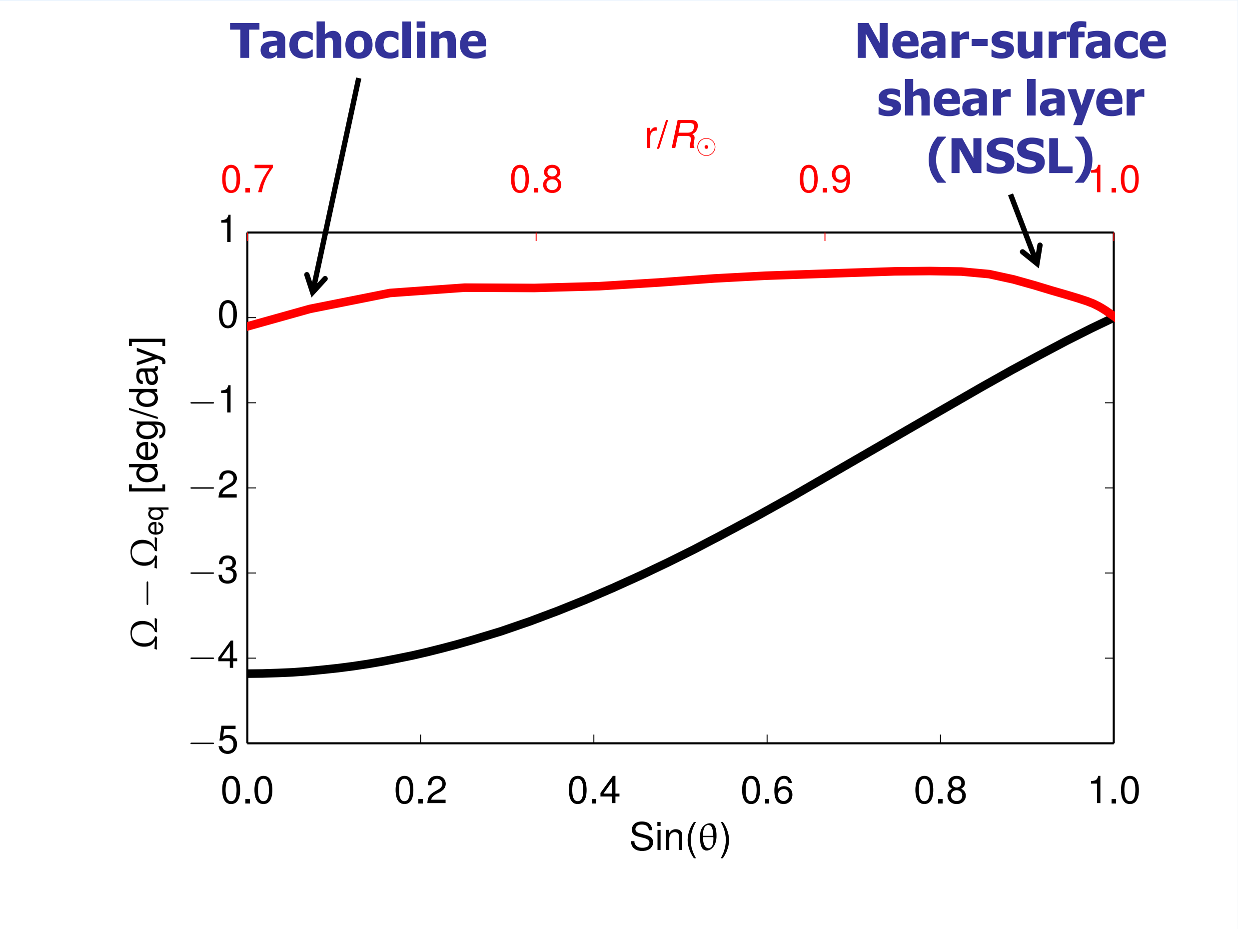
  2) toroidal field is generated by winding up of the poloidal flux connected to the polar fields by latitudinal differential rotation
     ← Hale′s laws, helioseismology, Stokes′ theorem

- Additional "turbulent" sources of poloidal field, as well as the tachocline and the NSSL do not play a significant role for the solar cycle.

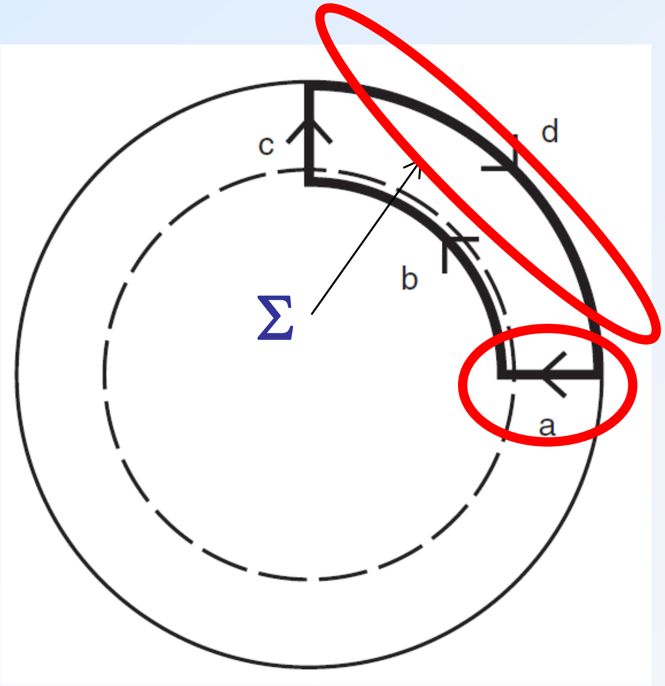
- The scatter in the properties (emergence location, tilt, …) of big active regions introduces a strong random element into the dynamo. This severely limits the scope for cycle prediction to predicting the amplitude of a cycle from the strength of the polar fields around the preceding minimum.

- Loose ends: location of the toroidal flux system in the convection zone, nature of flux emergence process and dynamo nonlinearity, confinement and equatorward migration of the activity belts, …

Contribution of radial differential rotation



Compare contributions from parts **a** und **d**



Contribution of radial differential rotation

$$\frac{\mathrm{d}\Phi^{\mathrm{N}}_{\mathrm{tor}}}{\mathrm{d}t} = \int_{\delta\Sigma} (\mathbf{U}\times\mathbf{B})\cdot \mathrm{d}\mathbf{l} = -\int_{r_0}^{R_\odot} U_\phi B_\theta \,\mathrm{d}r + \int_{\pi/2}^{0} U_\phi B_r R_\odot \,\mathrm{d}\theta\,,$$

a **d**

Part a: Assume 5×10^{22} Mx poloidal flux threading the NSSL

$$\left|\frac{\mathrm{d}\Phi^{\mathrm{N}}_{\mathrm{tor,NSSL}}}{\mathrm{d}t}\right| \approx 0.5(\Delta U_\phi) B_\theta \Delta r \approx 0.5(\Delta U_\phi)\Phi_{\mathrm{P}}/2\pi R_\odot \approx 1.3\cdot 10^{22}\,\mathrm{Mx\,yr^{-1}}$$

$$\Delta U_\phi \approx 7.5\cdot 10^3\,\mathrm{cm\ s^{-1}}$$

Part d: Assume 5×10^{22} Mx poloidal flux through 30 deg polar cap

$$\left|\frac{\mathrm{d}\Phi^{\mathrm{N}}_{\mathrm{tor,surf}}}{\mathrm{d}t}\right| \approx (\Delta V) B_r R_\odot \Delta(\cos\theta) \approx (\Delta V)\Phi_{\mathrm{P}}/2\pi R_\odot \approx 1.8\cdot 10^{23}\,\mathrm{Mx\,yr^{-1}}$$

$$\Delta V = |\Omega - \Omega_{\mathrm{eq}}| R_\odot \approx 5\cdot 10^4\,\mathrm{cm\ s^{-1}}$$

$$\left|\frac{\mathrm{d}\Phi^{\mathrm{N}}_{\mathrm{tor,NSSL}}}{\mathrm{d}t}\right| \Big/ \left|\frac{\mathrm{d}\Phi^{\mathrm{N}}_{\mathrm{tor,surf}}}{\mathrm{d}t}\right| \approx 0.07\,,$$